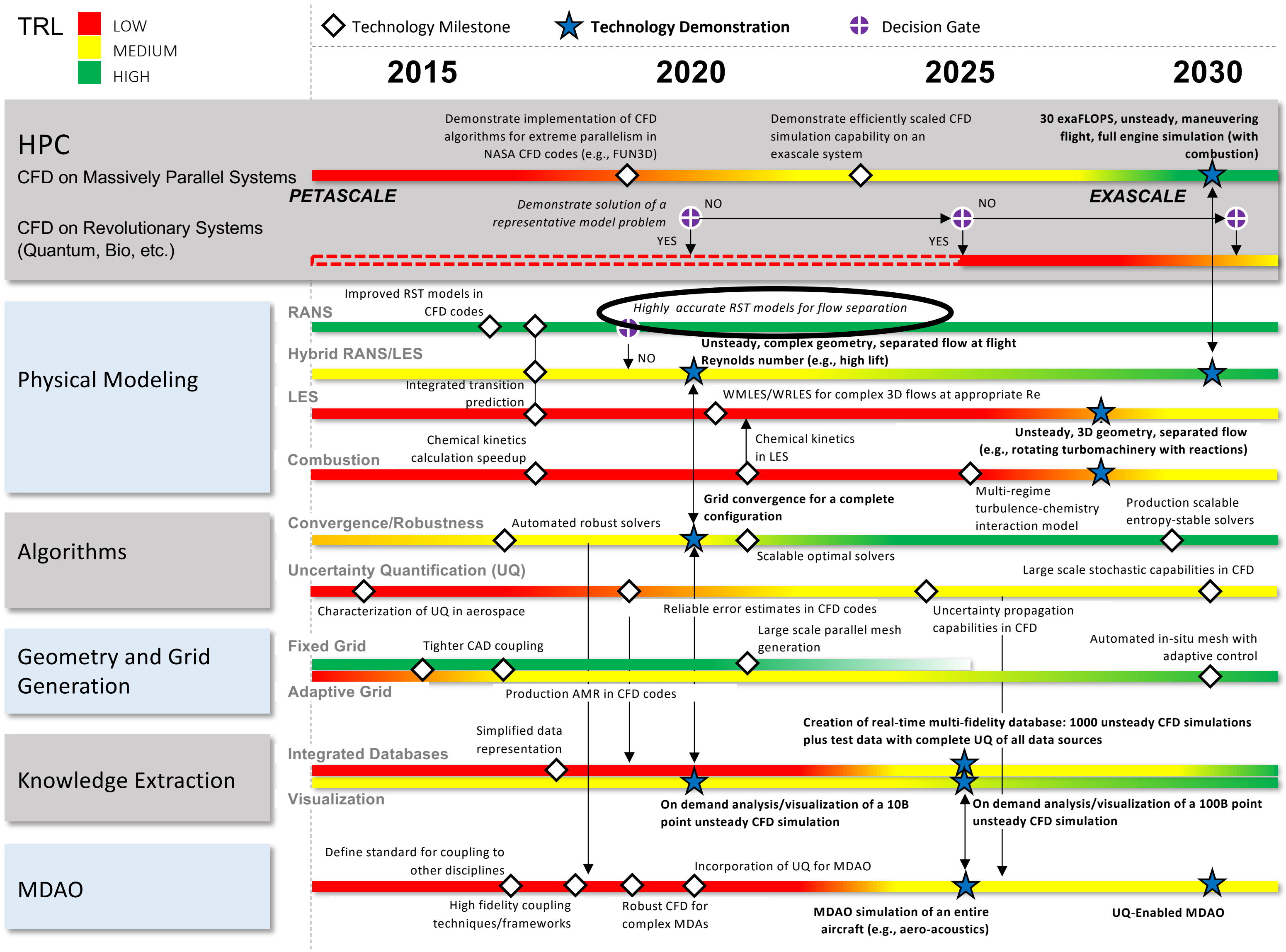
Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, September 12th, 2019

Turbulence Prediction in Aerospace CFD: Reality and the Vision 2030 Roadmap

Philippe Spalart and Mikhail Strelets

Background

- Discussion of the issues in physical modeling
  - Turbulence, not transition
- Emphasis on aircraft, and trend towards Certification by Analysis
  - Better, faster designs with less wind-tunnel time and no surprises
- Cruise condition under rather good control
  - Even buffet prediction is not impossible
- Hard regions of the envelope: high lift, stall, helicopters, landing gear…
- 2030 Roadmap was defined in 2014, with the following highlights:
  - Improved Reynolds-Stress models, 2018
  - Decision on continuing RANS research, 2019
  - Hybrid RANS-LES of high lift at flight Reynolds number, 2020
  - LES of high lift at flight Reynolds number, 2021
  - Demonstration on exascale machine, 2023
  - 30 exaflops by 2030



TRL
LOW
MEDIUM
HIGH
Technology Milestone
Technology Demonstration
Decision Gate
2015
2020
2025
2030
HPC
CFD on Massively Parallel Systems
CFD on Revolutionary Systems (Quantum, Bio, etc.)
PETASCALE
EXASCALE
Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)
Demonstrate efficiently scaled CFD simulation capability on an exascale system
30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)
Demonstrate solution of a representative model problem
NO
YES
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Physical Modeling
RANS
Hybrid RANS/LES
LES
Combustion
Improved RST models in CFD codes
Highly accurate RST models for flow separation
NO
Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)
Integrated transition prediction
WMLES/WRLES for complex 3D flows at appropriate Re
Chemical kinetics calculation speedup
Chemical kinetics in LES
Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)
Multi-regime turbulence-chemistry interaction model
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Grid convergence for a complete configuration
Production scalable entropy-stable solvers
Scalable optimal solvers
Large scale stochastic capabilities in CFD
Characterization of UQ in aerospace
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On demand analysis/visualization of a 10B point unsteady CFD simulation
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MDAO
Define standard for coupling to other disciplines
Incorporation of UQ for MDAO
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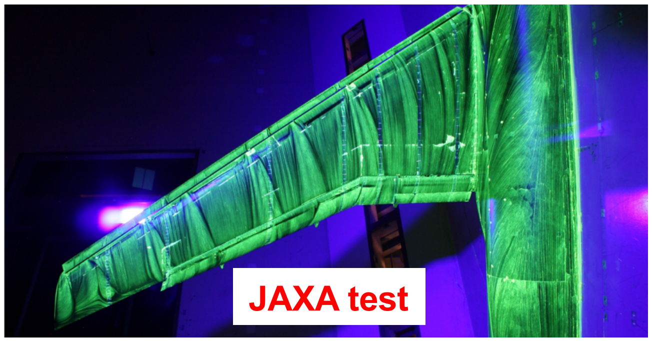
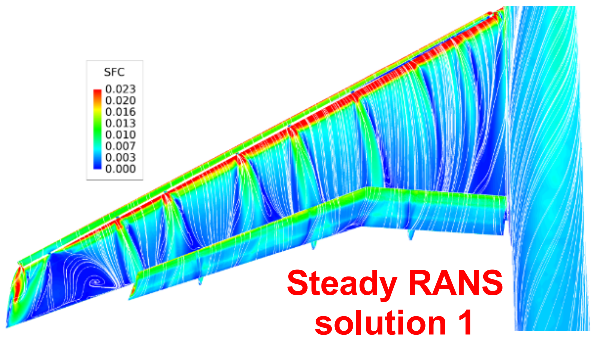
UQ-Enabled MDAO

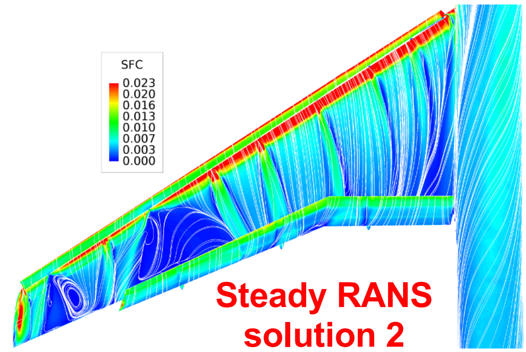
Achievements, 2014 to 2019

- Reynolds-Stress Models established in DLR and NASA codes.
  - Highly accurate? No. RSM's do not consistently improve over eddy-viscosity models
    - Especially SARC-QCR (-:
  - Convergence can be difficult
  - Models are almost static
    - Brief efforts by Rumsey and Spalart to alter SSG part not fruitful
    - See Eisfeld papers at this meeting
  - This appears to settle the "2019 Decision Gate"
- The Turbulence Modeling Benchmark Discussion Group, in a white paper, objects to stopping RANS research (AIAA-2019-0317, Bush et al.)
  - Cost of turbulence-resolving methods
  - Wide expectations that Artificial Intelligence will revolutionize RANS field
- Steady RANS models and codes plagued by multiple solutions
  - Worst symptom is "pizza slice" wide separation behind slat brackets
    - Insensitive to model and algorithm, much more sudden than in wind tunnel

The Slat-Bracket Problem (“Pizza Slice”)



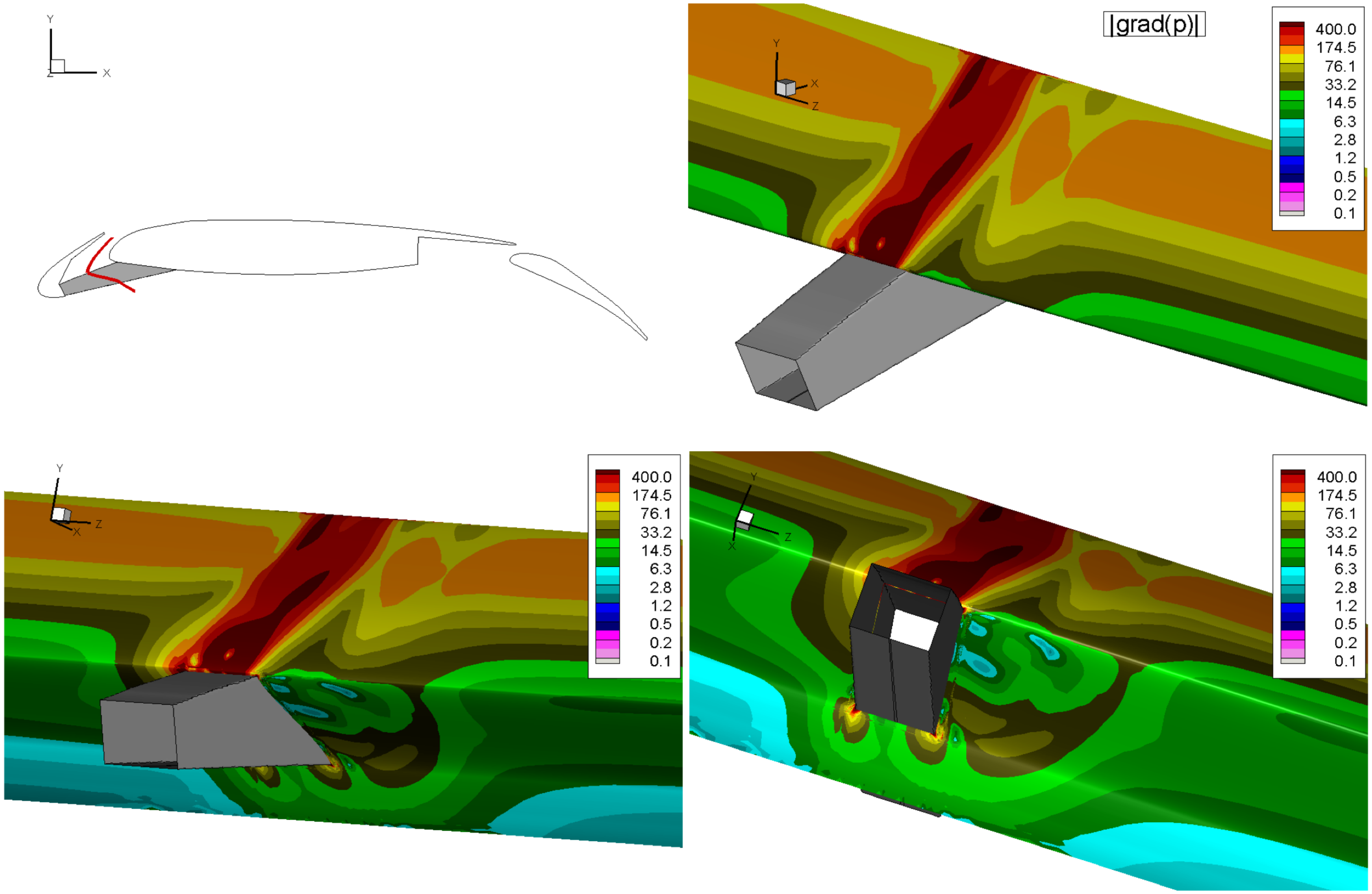




AIAA 2018-1037. Cary, Mani, Yousuf, & Li

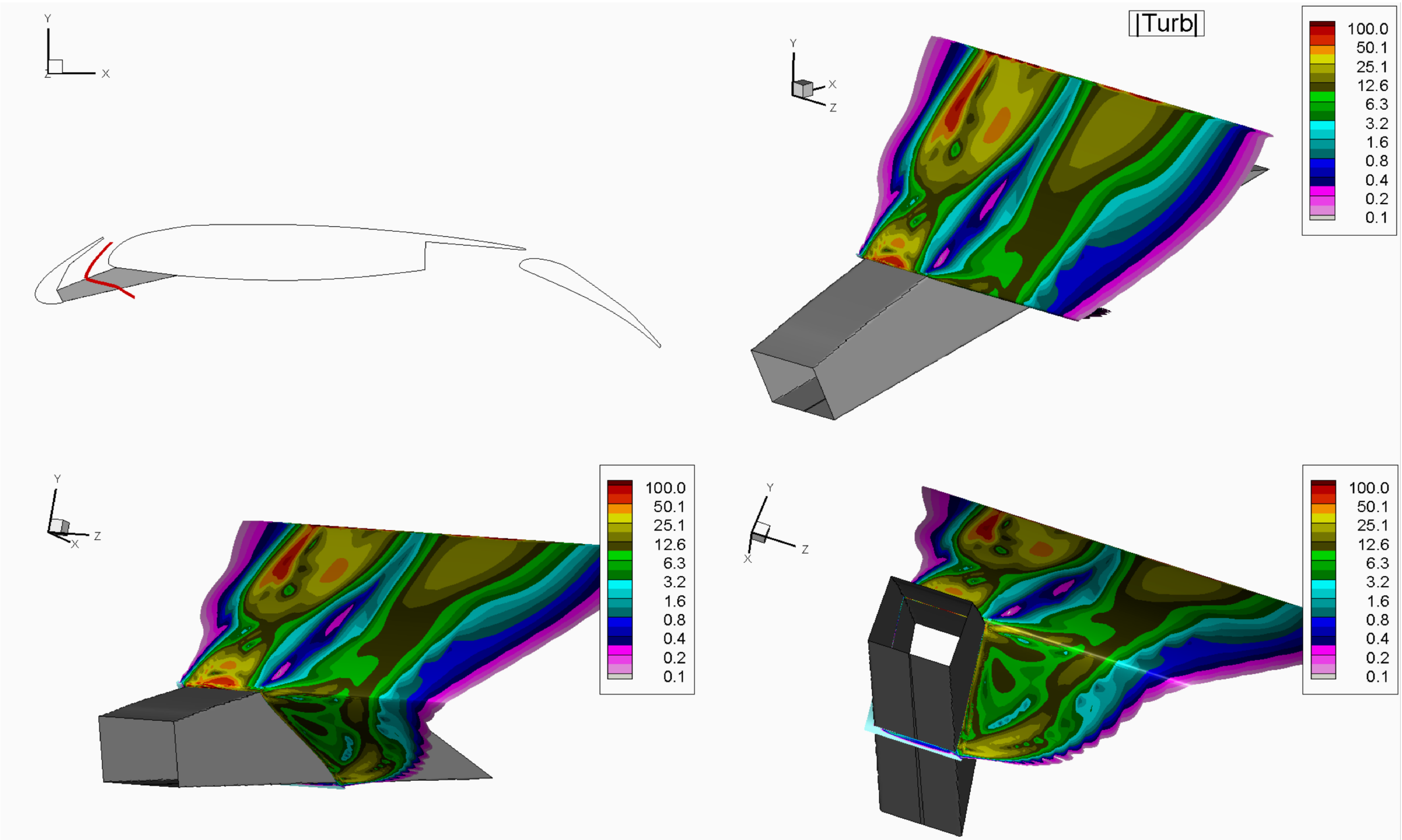
- The key question: can RANS models be made to work well enough?
- The phenomenon appears to be spurious, or at least premature
- It cuts across turbulence models and codes
- It is agreed that we don’t have grid convergence, but grid adaptation failed to suppress it
- Is it a “robust consequence” of the steady RANS equations?
- Do the models **cause** it, or are they only too weak to suppress it?
- Is the bracket region “violently 3D, essentially convecting and rotating vorticity?”

Pressure-Gradient Term in Momentum Equation



Time-average of a URANS

Reynolds-Stress Term in Momentum Equation



Time-average of a URANS

Turbulence Models in Simple Flow

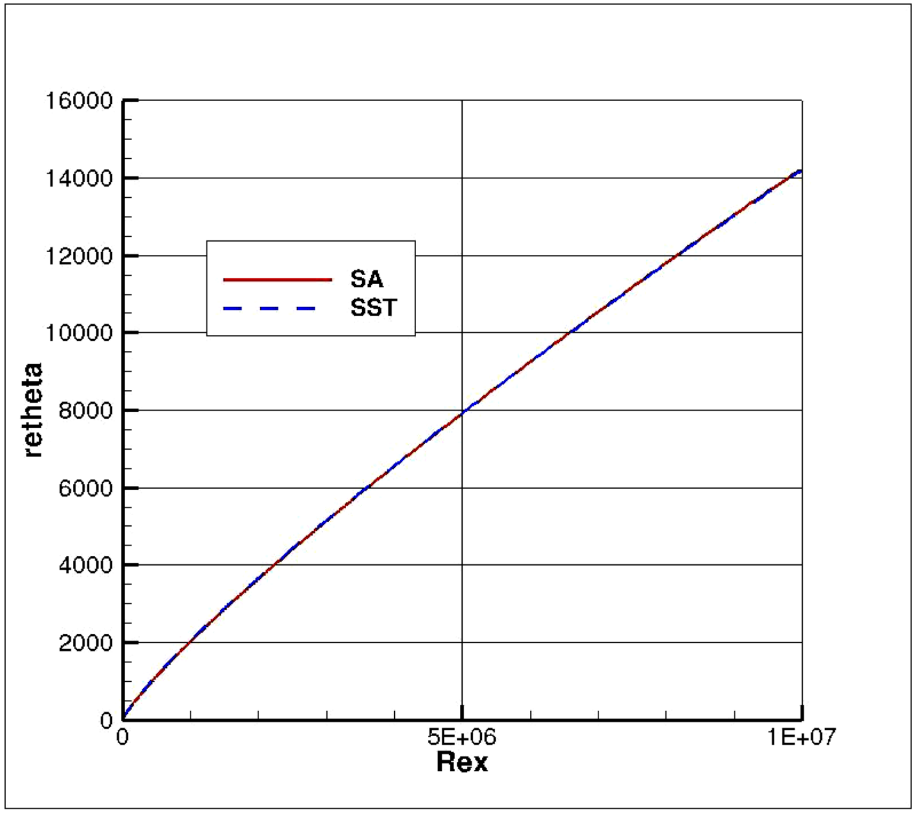
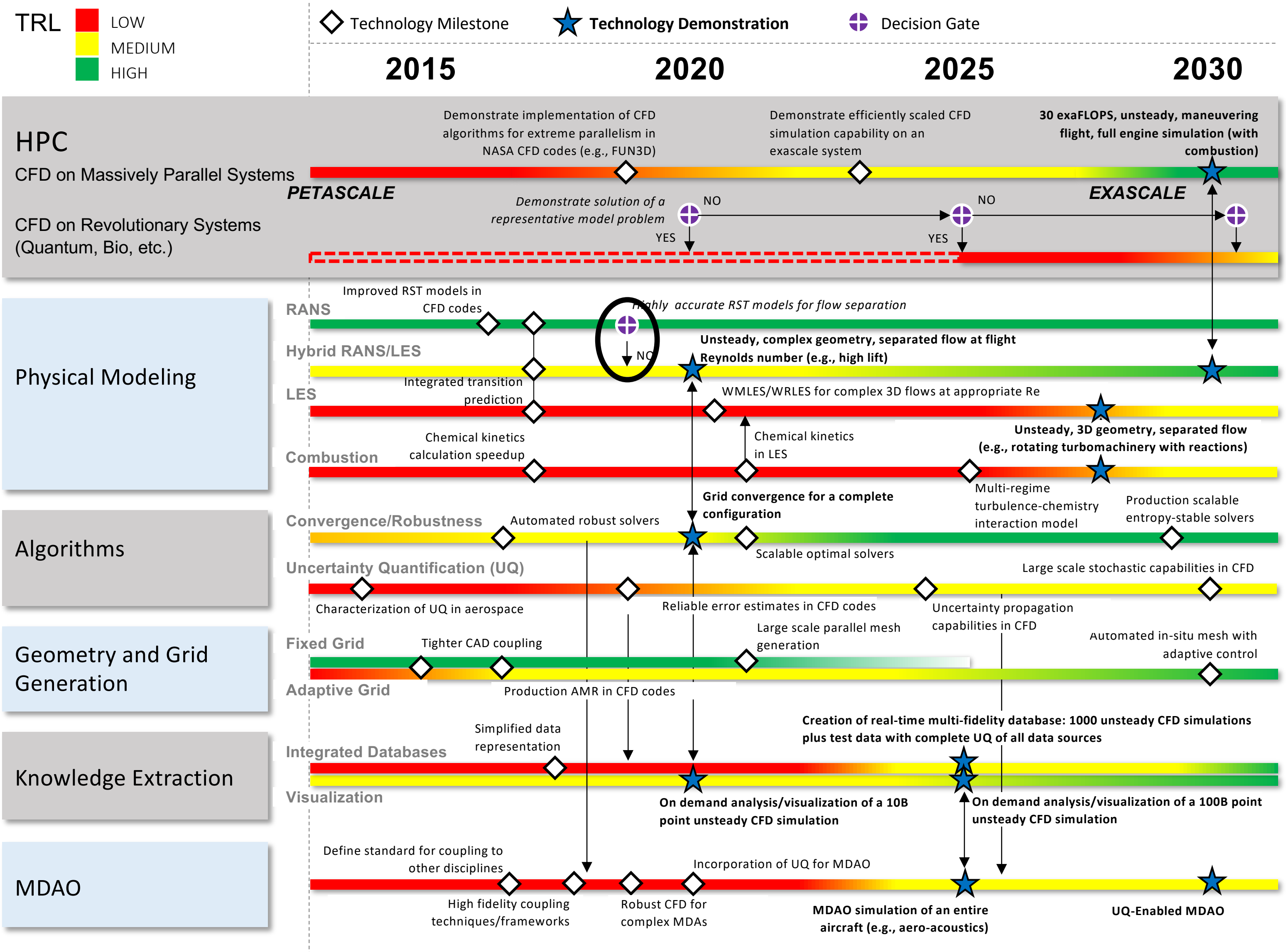


Figure from TMR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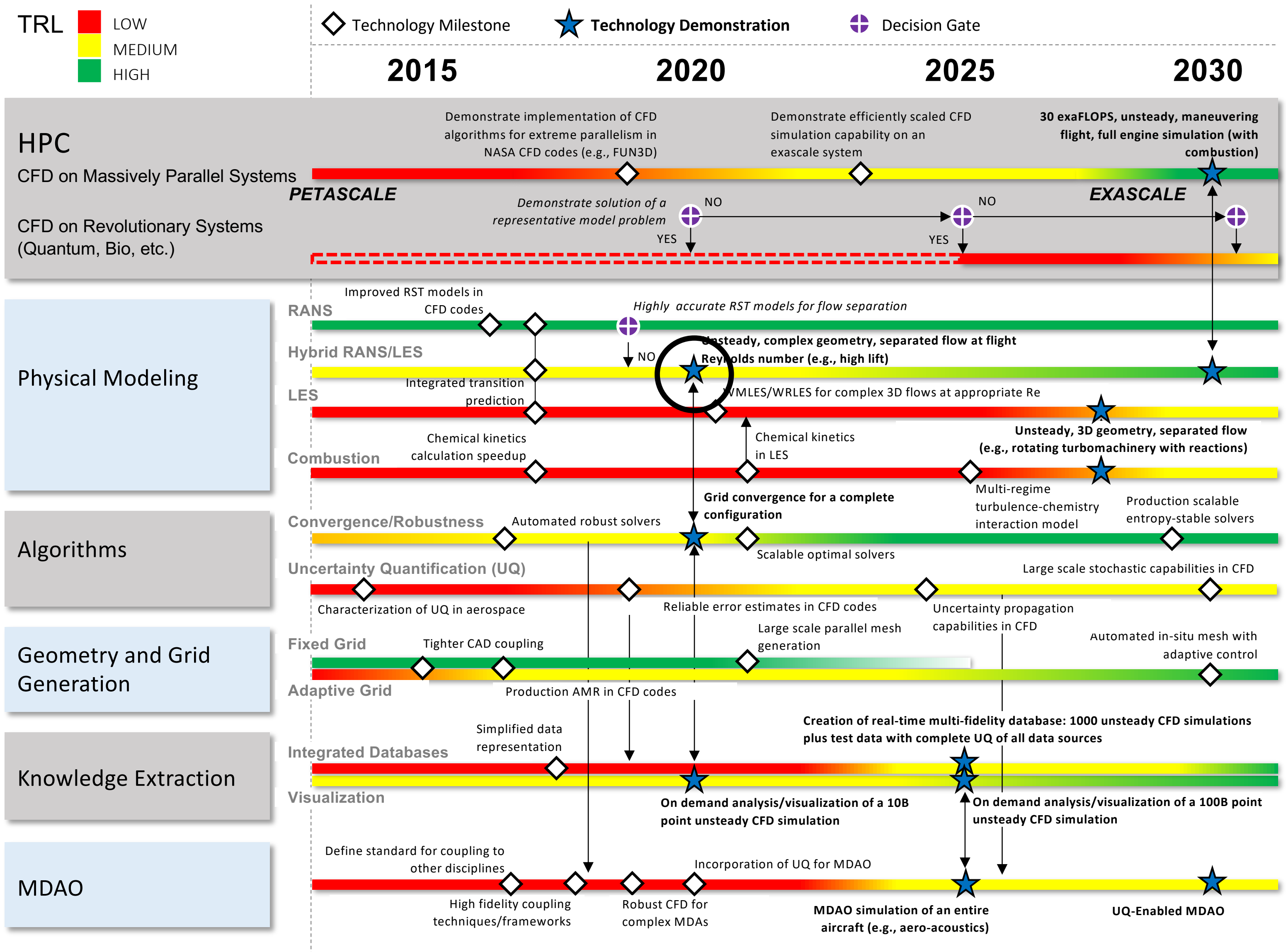

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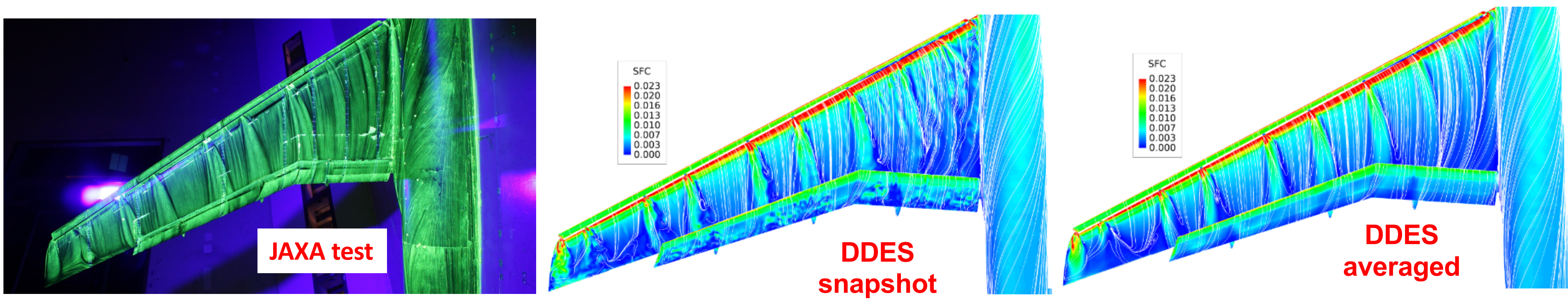
Preliminary Success of DDES at 3rd High-Lift Workshop

- Turbulence-resolving approaches appear immune to pizza slice issue
    - DES, WMLES, LBM-VLES…
- They tend to give better lift than RANS near Clmax
- No reports of multiple solutions, from “cold starts”



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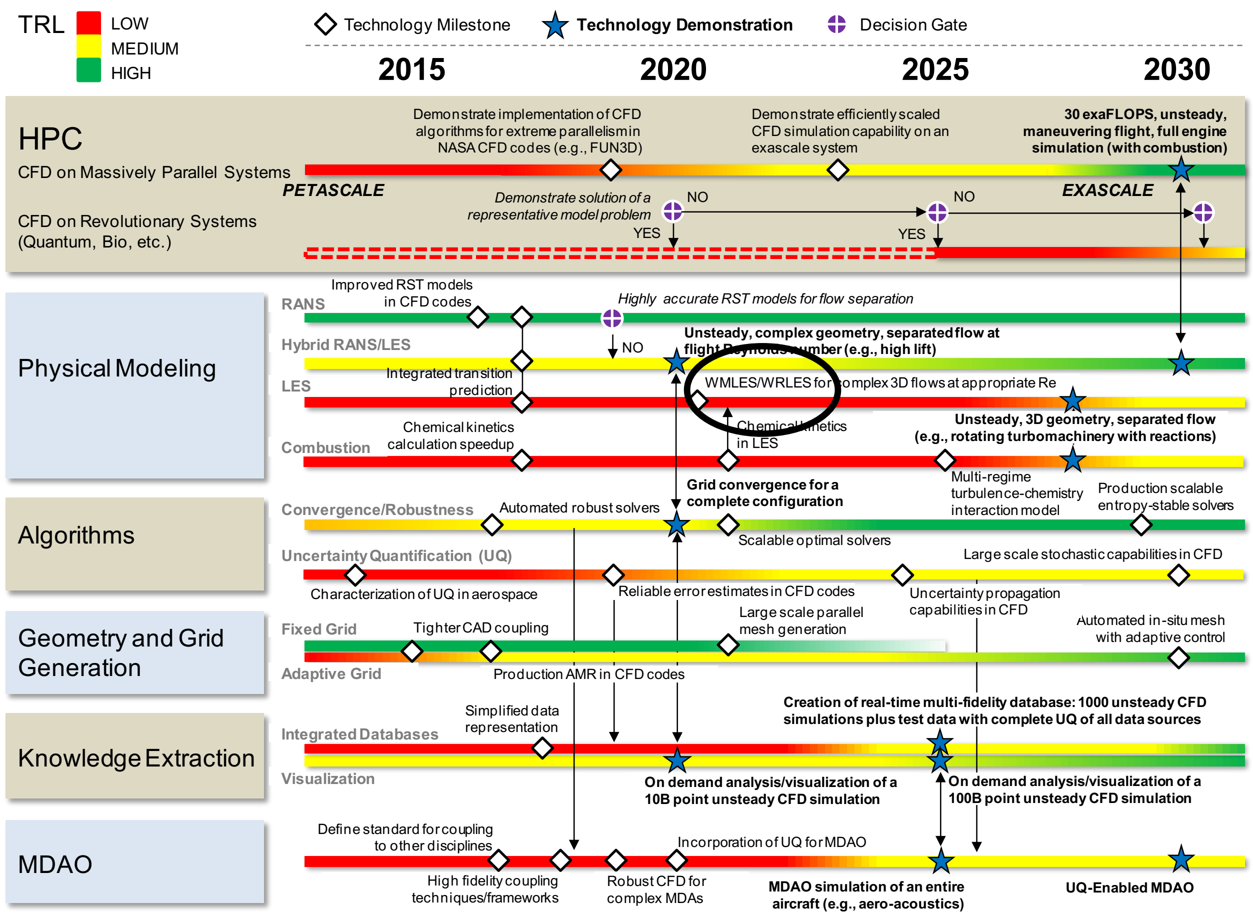
CFD Vision 2030 Roadmap



2014-2019 Activity: Wall-Modeled Large-Eddy Simulation

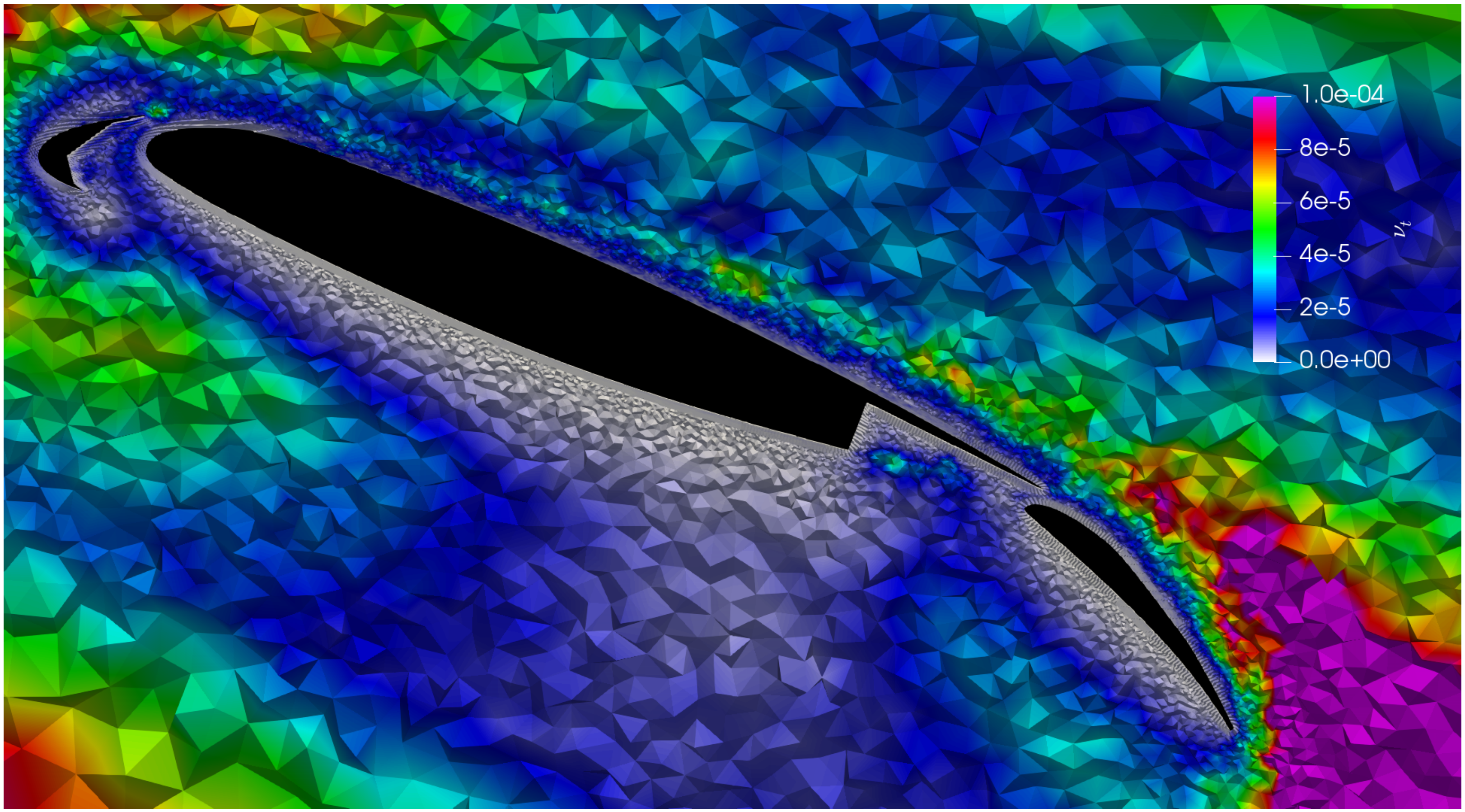
- Some people consider WMLES to be "turn key," just expensive
  - The "N_{cubes} Problem" remains: in the thinner BL regions, the WM does everything
- It has given encouraging results for high lift, compared with RANS
  - Particularly at Stanford and Barcelona; PowerFLOW and PHASTA are similar
- For simple shear flows, channel and TBL, WM is the key difficulty
  - The SGS model proper has been validated, and is not very sensitive
- *Not so* for external flows with "real" geometries

$$\nu_{SGS} = f\left(S_{ij}, grid\ cell\right)$$

  - This is innocuous at the end of the inertial range in a turbulent region
- Real flows have strain and grid variations in regions that should be inviscid and irrotational
  - The non-uniform SGS viscosity then creates vorticity
  - However, numerical errors also do… (private comments of Lehmkuhl and Rodriguez)
- The SA and SST-V models, used in DES, do not have this problem
  - The PDE also improves the smoothness of the eddy viscosity
  - ILSA also seems largely immune

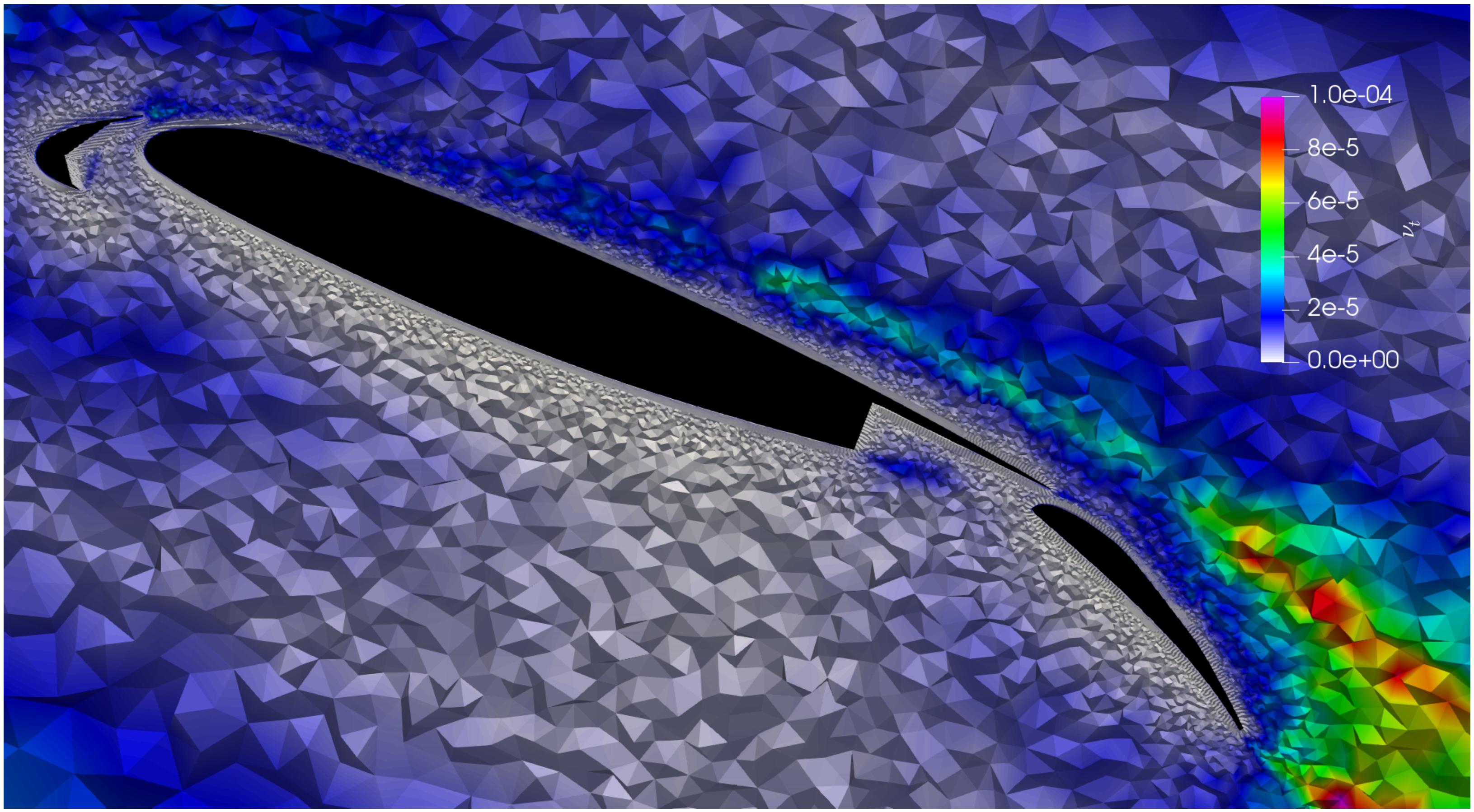
SGS Eddy Viscosity of Vreman Model

- Work of O. Lehmkuhl, Alya code



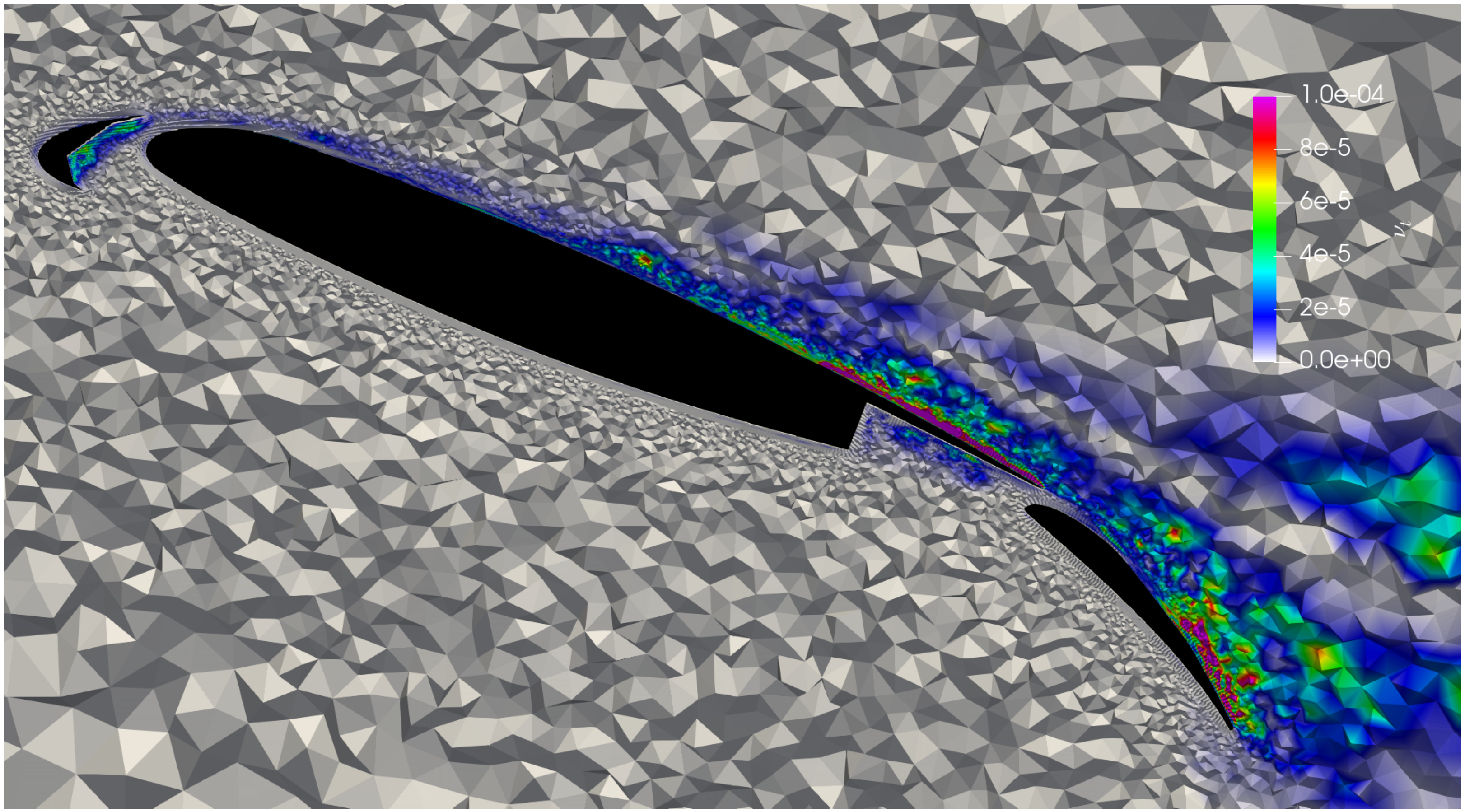
SGS Eddy Viscosity of Smagorinsky Model

- Work of O. Lehmkuhl

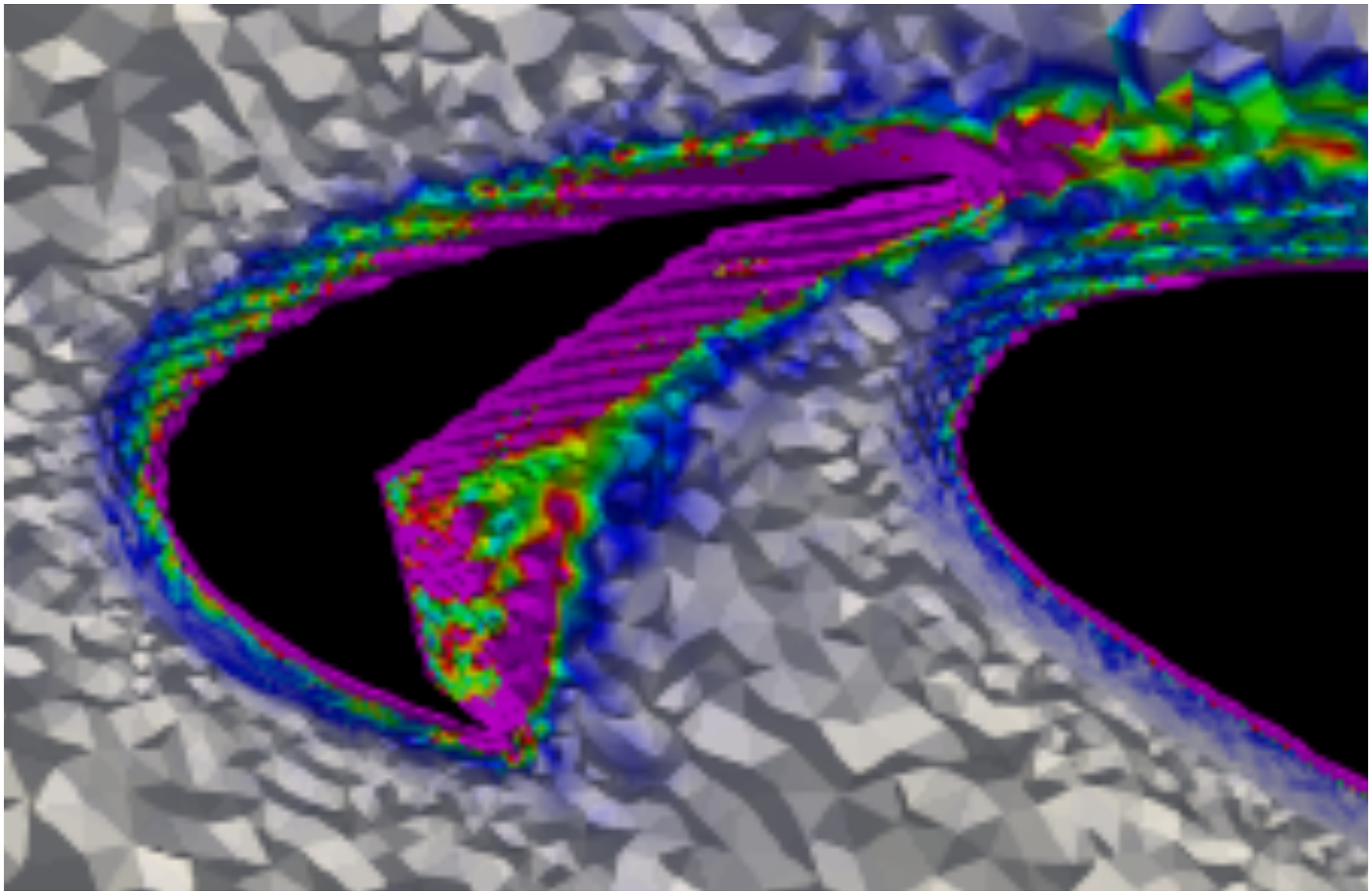


SGS Eddy Viscosity of ILSA Model

- Work of O. Lehmkuhl with U. Piomelli



Vorticity with Vreman Model



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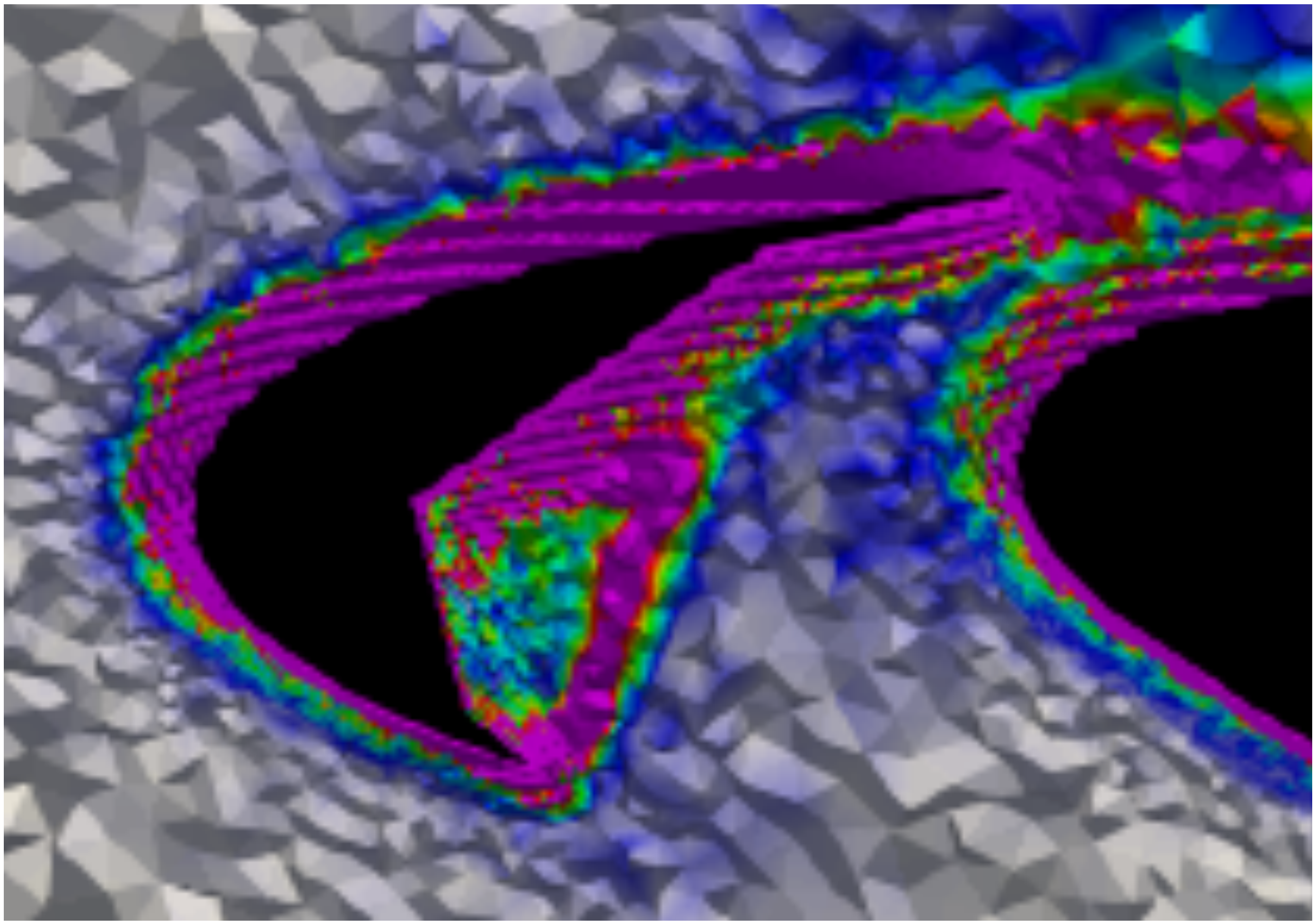
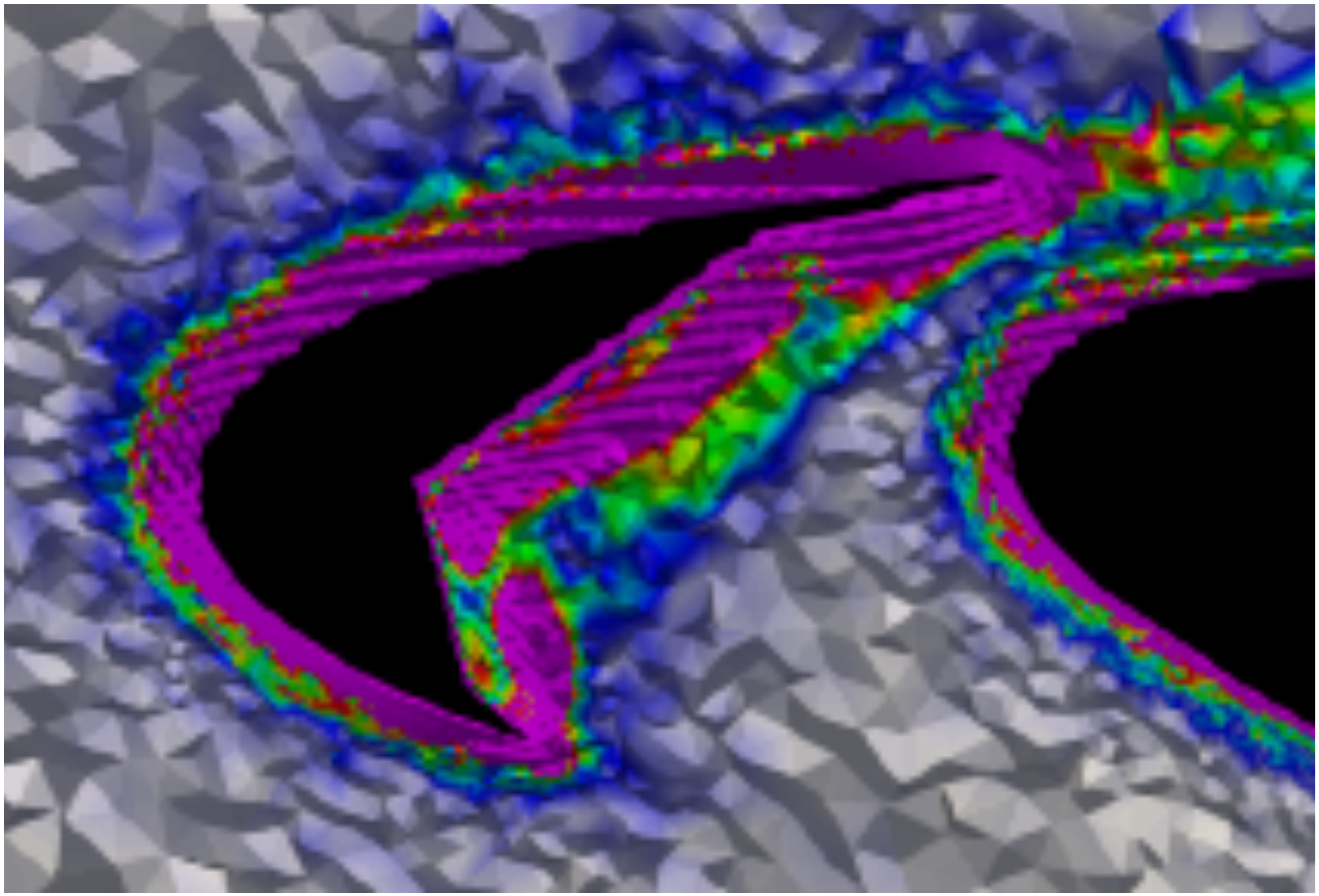
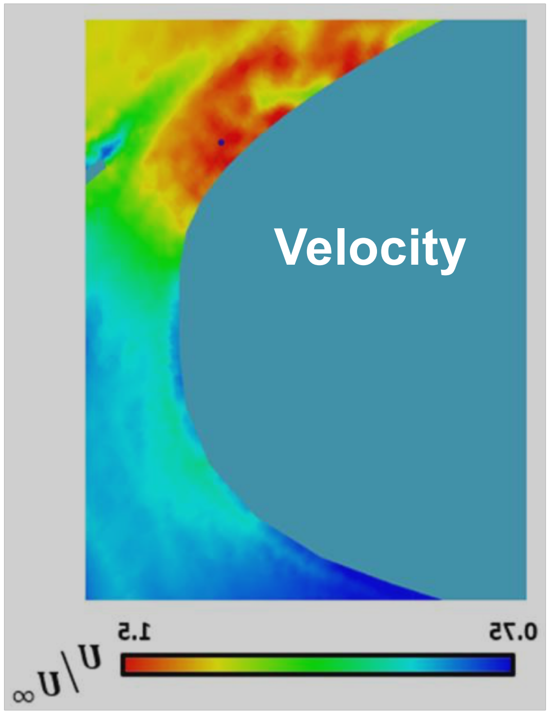
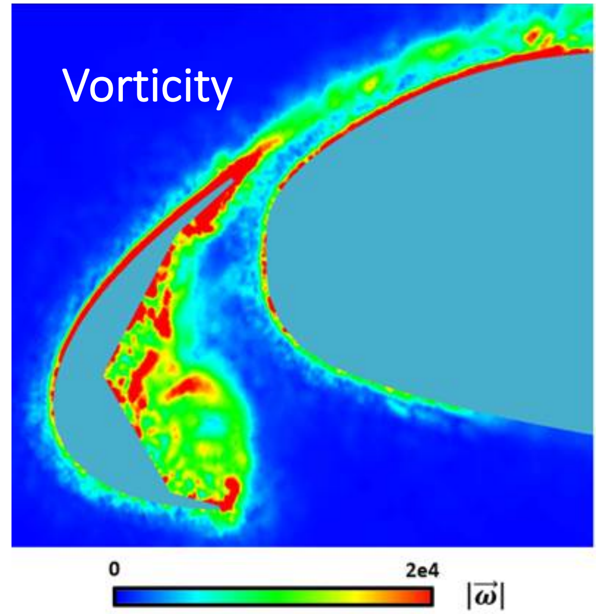
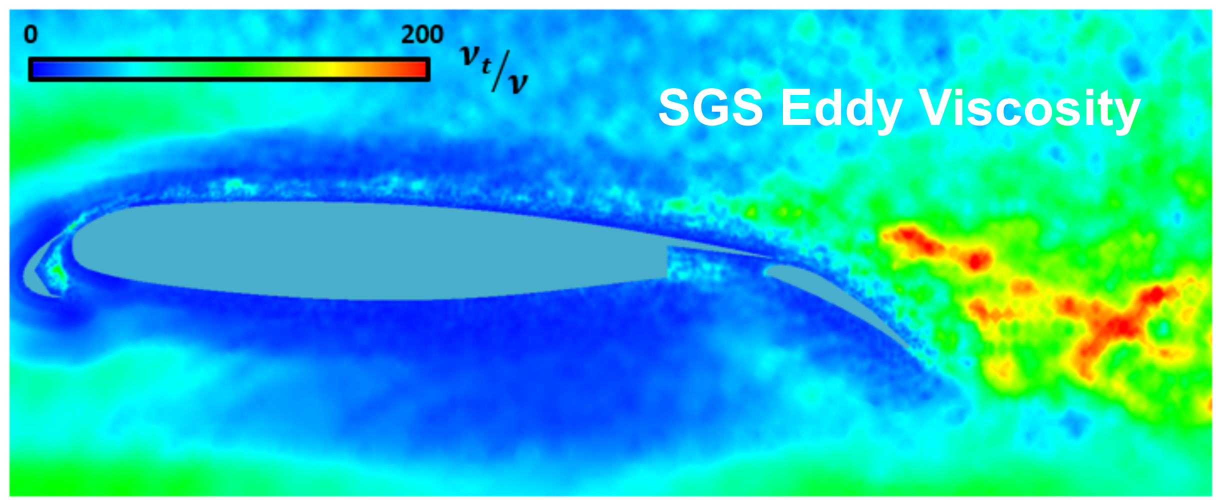


Vorticity with ILSA Model





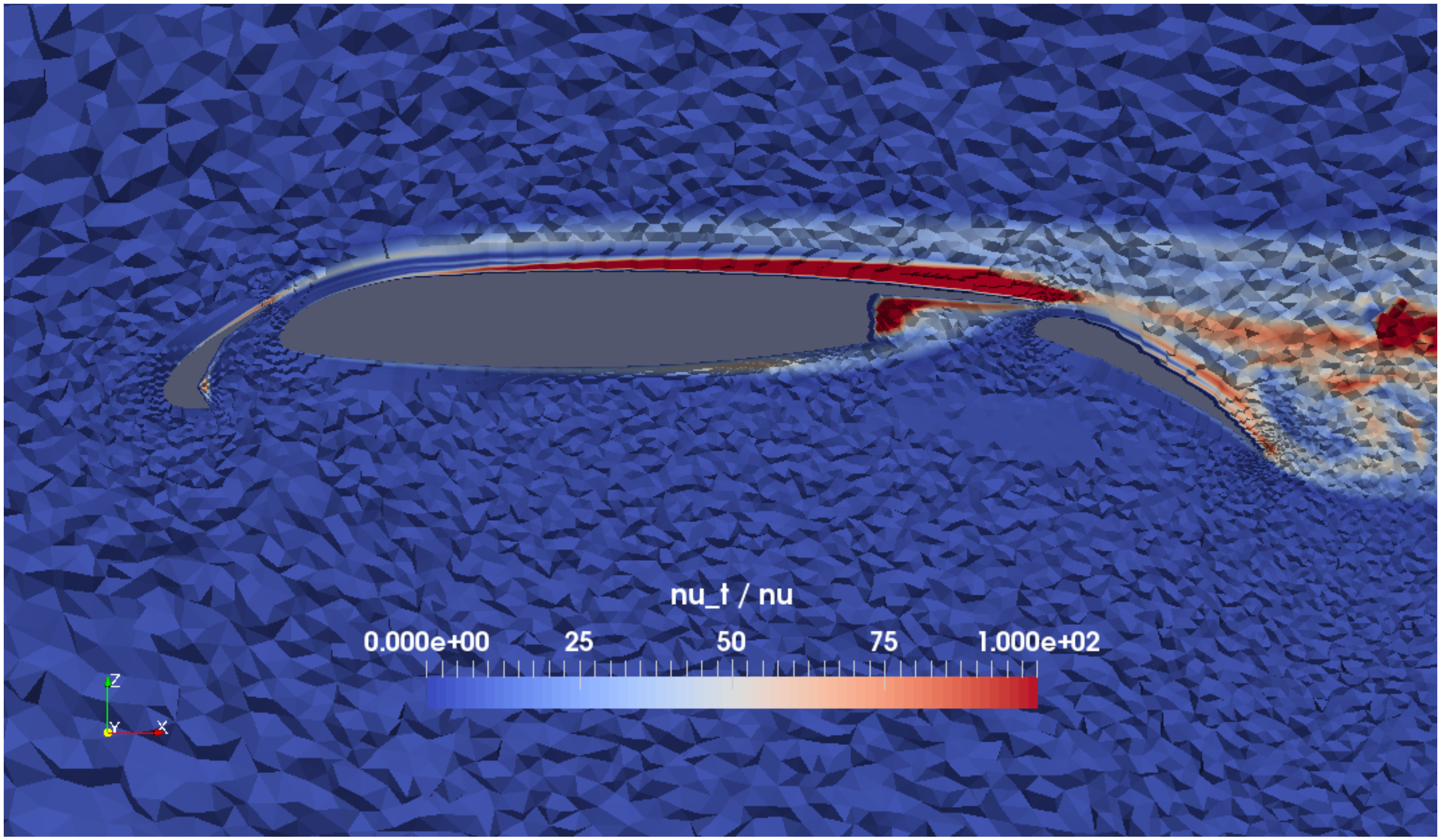




- Work of K. Goc and P. Moin
  - ➢ CharLES code, Vreman model
  - ➢ Slip WM

DDES Eddy Viscosity

- Work of R. Balin and K. Jansen, PHASTA code



DDES Vorticity

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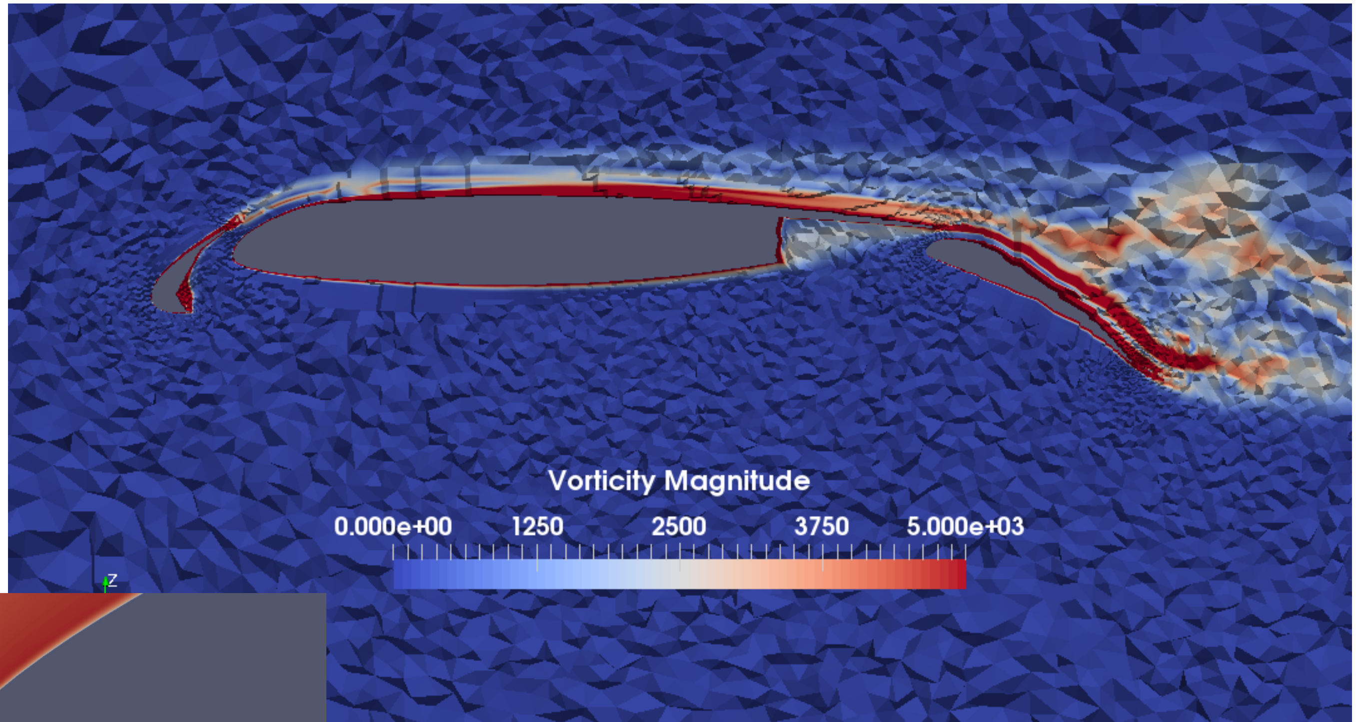
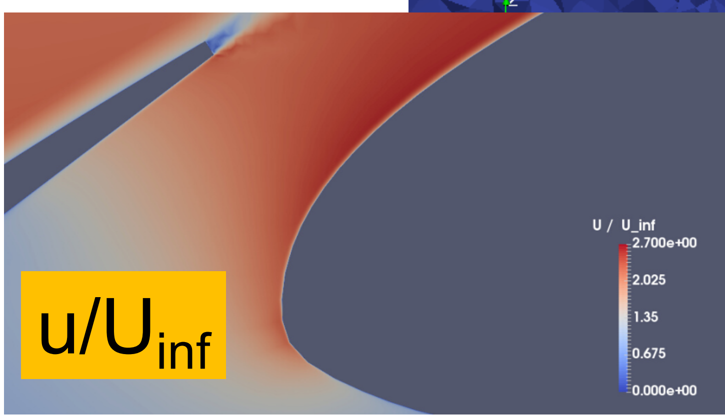
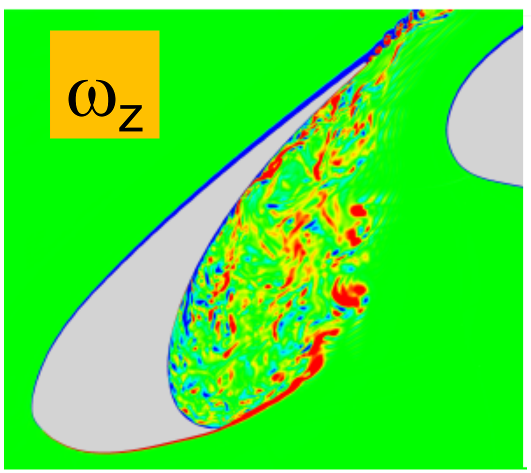
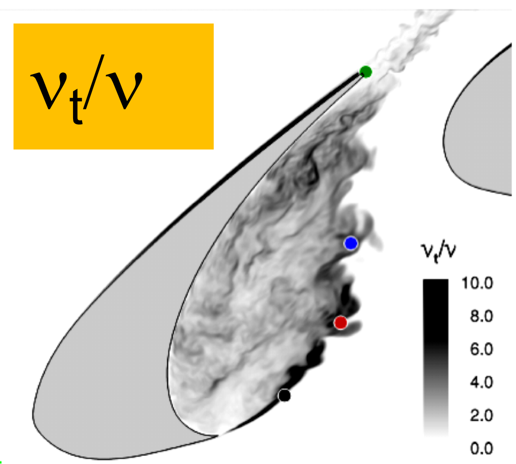


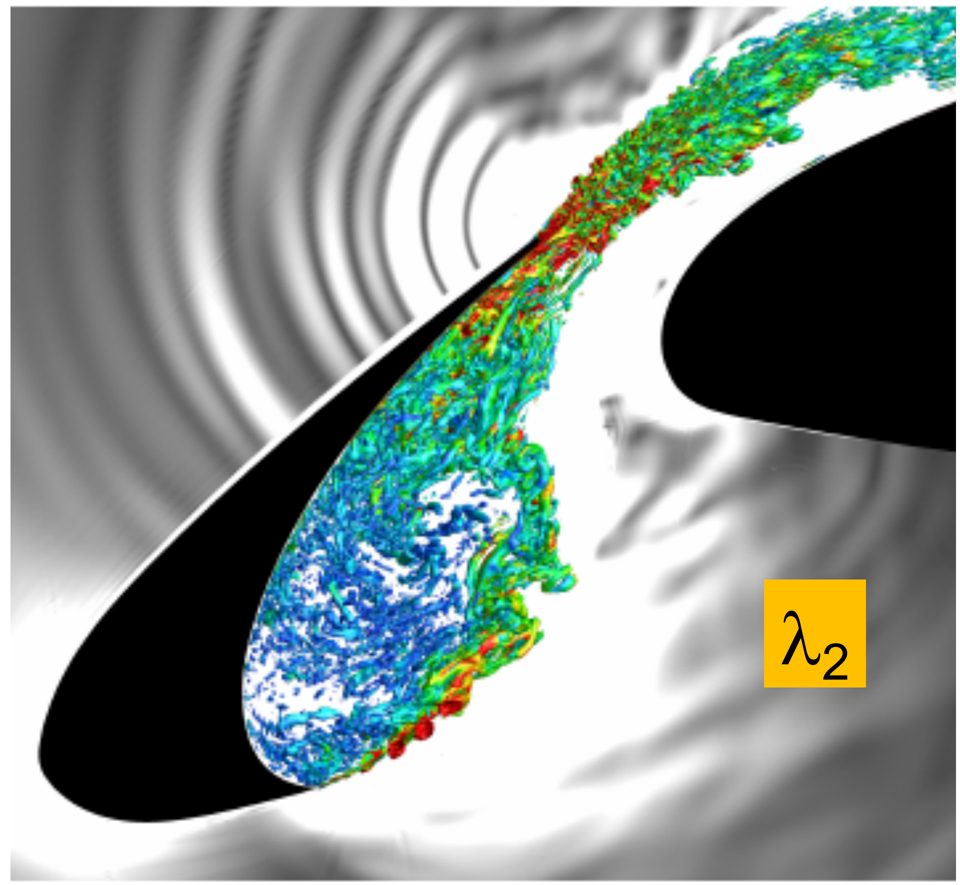


Narrow Slice Simulation

- Work of T. Knacke and F. Thiele (2013-2162)
- DDES in ELAN code
- Width 3.3% of chord (30P30N)
  - 9M points in cove
  - Time sample 70,000 steps, T ~ 8 c / U
- Real problem is hundreds of times larger
  - Lemkuhl had 70M points and 193M elements for the half airplane







Artificial Intelligence in Turbulence Modeling

- AI has made great strides in extremely difficult areas such as translation
  - Tools proposed here include Machine Learning, Big Data, Deep Neural Networks, etc.
  - Many paper titles sound like: “Physics-Informed Machine Learning Approach for Augmenting Turbulence Models: A Comprehensive Framework”
- RANS modeling arguably has stagnated for decades
  - In Aerodynamics. Not as much in internal flows?
  - It’s possible that RANS modeling faces a “Fundamental Paradox” and has an “Accuracy Barrier,” and the community’s expectations/the demands of CFD are not realistic (local model formulation)
  - The SA and SST models are very useful, but not founded on theory or DNS
- There is logic in hoping AI can end the stagnation, with two threads:
  - 1. New thinking, new terms, new physics, some based on DNS data
  - 2. More powerful optimization of existing models over a wide range of flows
- Should this include “historical” modelers, or start from a “clean sheet of paper?”
  - Many “clean sheet” efforts violate Galilean Invariance, or have more subtle defects
  - A very clear “mission” must exist
  - Very few code-ready new models, or model versions, have been produced so far
    - Except by Weatheritt & Sandberg, using Genetics of the equations!
  - Note that Symbolic Manipulation of equations has not caused much progress
- A large European proposal, HiFi-TURB of Hirsch & Haase, hinges on this hope
  - Kick-off meeting in July 2019! Historical modelers very much included, and NASA

Summary

- Since 2014, our community's work has been collaborative and smart enough
  - Experimentalists, numerical types, and modelers
- Budgets are not matching the value of and the promises made for CFD
- The growth of computing power has slowed badly
- For high-lift, modeling can still hide behind the lack of grid convergence
  - Yet, it is certain modeling will become the "tent pole," in the steady RANS setting
- Traditional turbulence modeling is challenged from two sides:
  - Turbulence-resolving simulations
    - These are promising, but far from industry practical. We need **many** exaflops
    - The flow fields have some very "interesting" features…
    - We contend that DES is cleaner, and will deliver well before WMLES and VLES
  - Artificial intelligence
    - We contend that this work is still in its infancy, and much of it is simply unsuccessful
    - A lot of "adult supervision" is needed
    - Did we the "adults" fail to explain modeling (too bad Wilcox's book is now rare)?
- Several of the Vision 2030 milestones will be missed